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# A SEPARATION PRINCIPLE FOR AUTOMATIC CONTROL SYSTEMS DESIGN

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ABSTRACT. Linearization and feedback are two classical techniques for automatic control systems design. They, however, do not result in controllers which can drive highly nonlinear systems to follow rapidly varying trajectories. A new apporach has been developed in a NASA project: Totally Automatic Flight Control Systems. Two key ideas are underlying the new method. Firstly, nonlinearity-preserving transformation is used to linearize system dynamics for facilitating linear controller design. Secondly, controller design has two parts: the steering controller which does the basic planning and control and the regulating controller does the necessary correction due to disturbances and modelling error. This article emphasizes the second idea, which is called the separation principle. The advantage of a controller designed on this principle is demonstrated by showing that the classical tradeoff of command following and sensitivity, reduction is largely avoided.

1. INTRODUCTION. A research project at NASA Ames Research Center called Totally Automatic Flight Control Systems has recently attracted much attention among the researchers in the control community. The objective of this project is to design automatic flight controllers which are capable of piloting the vehicles to meet flight trajectory commands exogenously given. Although the goal sounds similar to that of conventional autopilots, the classical design techniques have proved to be inadequate because the following situations are faced by TAFCOS:

(1) The vehicles to be controlled are highly nonlinear.

(2) Fast responses are to be achieved.

Two important techniques used in classical design of automatic controllers are linearization and feedback. A feedback controller is essentially designed to be driven by error signals formed by the desired response and the actual response of the system. This is done so that the error will diminish in a manner which satisfies the design specifications and physical constraints.

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The direct input driving the system is obtained indirectly as the output of the controller. During design great effort must be spent in unavoidable tradeoffs among the sensitivity of the closed-loop system to disturbances, sensitivity to measurement noise, steady-state error, and the speed of the response.

Most of our understanding of and design techniques for feedback design center around linear systems. Ordinarily a nonlinear system needs to be linearized by a series expansion and truncation of second and higher order terms. With the system model being linearized at several chosen operating points, a global nonlinear model is approximated by a finite set of local linear models. Linear techniques are then applied to design a local linear controller for each such model. To successfully control the vehicle, the local controllers need to be tied together. A procedure generally known as gain scheduling is used for switching from one controller to another when the system's state moves across various boundaries.

2. TOTAL AUTOMATIC FLIGHT CONTROL SYSTEMS (TAFCOS). TAFCOS was introduced to attack the problem of automatic control of aircraft having short take-off and landing capabilities [1]. The vehicles are highly nonlinear and the automatic controller must be designed to take advatnage of their nonlinear dynamics. If classical linearization is applied for highly nonlinear operations such as take-off or landing, a great many linear models are required. The typical result is a large set of linear controllers and a very complicated gain-scheduling scheme. Moreover, the nonlinear operation rapidly leads the system from one linear locality to another. The controllers must produce very fast responses, and this is difficult to be achieved by the fixed-structure-driven-by-error controllers due to the tradeoffs involved in design.

Motivated by these difficulties TAFCOS proposes two new design ideas:

(1) Instead of designing controllers based on local linearity, a nonlinear transformation of the state variable and input is sought so that the nonlinear dynamics becomes linear in terms of transformed state and input. If this can be done, a canonical linear system can be fixed as the target of this transformation; the transformation will reflect the individuality of the nonlinear system, but the linear dynamics is invariant. Linear controller design can then be based on this canonical linear model.

(2) The controller is composed of two parts: one computes the basic control input that drives the system to best fit the command, and the other guarantees that the system stays on course in spite of disturbances, modelling error, etc.

To illustrate, a generic design structure of TAFCOS is depicted in Figure 1, where $(x,u)$ and $(y,v)$ are the respective states and controls for the nonlinear and linear systems.

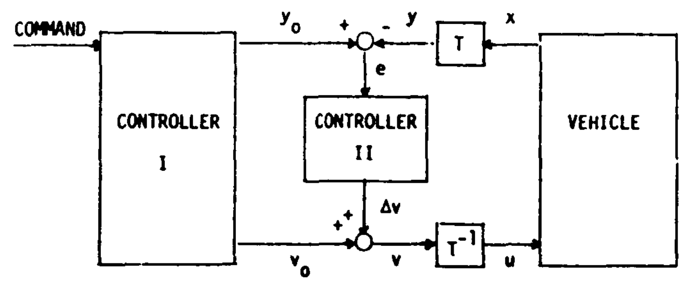


Figure 1

Here $T$ represents the transformation from the nonlinear system to the linear system, and $T^{-1}$ is its inverse. The outputs $v_0$ and $y_0$ from Controller I are the basic control and the trajectory to be followed. The vehicle's trajectory $x$ is transformed to $y$ and is compared with $y_0$ to form an error e. Controller II is driven by e to generate correcting control $\Delta v$. The sum $v = v + \Delta v$ is transformed back to the natural control $u$ of the system.

The transformation aspect of TAFCOS design has been vigorously studied by many authors. Useful results can be found in references [2,3,4]. In the rest of the article we want to discuss the controller design of TAFCOS, which is probably the more important idea of the two ideas for TAFCOS mentioned earlier.

3. SEPARATION PRINCIPLE FOR CONTROLLER DESIGN. To recapitulate what we mentioned earlier, a conventional feedback controller (for steering a vehicle to meet commands) is designed on the following principles:

(1) It is error-driven.
(2) Design specifications are translated into structural requirements for the closed-loop system such as pole-and-zero configuration, stability margin, etc.
(3) The function of the controller to steer the vehicle to meet commands is done by regulating the error signal, and satisfactory regulation is accomplished by structural design.

In TAFCOS design a fundamentally different set of concepts is adopted, and provides us with "the separation principle for controller design" and states as follows:

(1) Basic steering and regulating should be accomplished by two separated controllers.

(2) The steering controller is to be driven by the command and generates a basic control and the resulting response of the system. The response that meets the command and together with the control are acceptable (or even optimal) on the basis of a priori knowledge about the system and the environment such as system model and noise model.

(3) The regulating controller is error-driven and regulates the system to follow the trajectory generated by the steering controller by contributing an incremental control to the total control.

(4) The total input to the system is a sum of the basic control generated by the steering controller and the incremental control.

Intuitively speaking, the steering controller controls the system based on our knowledge, and the regulating controller controls the system to reduce the impact of what we do not know.

This design structure has many advantages:

(1) The computation in the steering controller is basically free from the environmental disturbances and measurement noise. As a result we have more freedom in its design.

(2) It is easy to prevent the actuator from saturation with such a design. Whenever an exceedingly large error between the actual state and the trajectory to be followed is encountered, the steering controller can be instructed to recalculate an acceptable trajectory within the physical capability of the system.

(3) The steering controller can also be equipped with other capabilities such as adaptiveness to cope with changes in system's parameters.

Although there are standard techniques for regulator design, the design of steering controllers as such is a wide-open problem. Currently, NASA researchers are experimenting with the ideas of fixed feedback structure [5], and optimization [6] in this design problem. These are by no means the only possibilities. It is felt that a new look at this problem, which is completely free from the traditional attitude of regulator design, is needed.

To conclude this article, we demonstrate a benefit of the separation principle by showing that the classical conflict between low sensitivity and fast response can be largely avoided in TAFCOS controllers.

Let us consider the problem of designing an automatic positioning controller for a system having transfer function $G(s)$. A classical design with unity feedback is shown in Figure 2, where $C(s)$ is the controller.

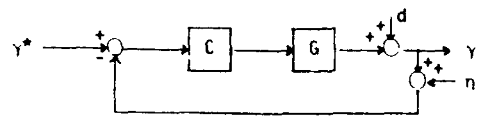


Figure 2

The system's response $\gamma$ to the command $\gamma^*$ can be expressed as

$$\gamma = \frac{CG}{1 + CG}\gamma^* - \frac{CG}{1 + CG}\eta + \frac{1}{1 + CG}d \quad ,$$

where $\eta$ is the measurement noise and $d$ the disturbance. A classical conflict exists between high loop gain to achieve good command following and low loop gain in order not to aggravate the measurement noise. This can be seen by noticing that if

$$|CG| >> 1, \quad \text{then} \quad \left|\frac{1}{1 + CG}\right| \sim 1 \quad ,$$

which reduces the error between $\gamma$ and $\gamma^*$, but also let $\eta$ freely pass to the response $\gamma$.

The conflict can be reduced by a TAFCOS controller design described in Figure 3.

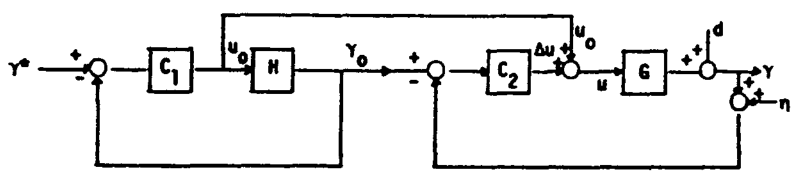


Figure 3

Here the system from $\gamma^*$ to $\gamma_0$ is a steering controller, which is designed with a model $H$ of the $G$. Its output $u_0$ serves as the basic control of the system. We remark that the feedback structure inside the steering controller with a block $C_1$ is a computational scheme, which should not be confused with the actual feedback. The block $C_2$ represents the feedback regulating controller. Computing, the response $\gamma$ can be expressed as

$$\gamma = \frac{H^{-1}G + C_2G}{1 + C_2G} \cdot \frac{C_1H}{1 + C_1H}\gamma^* - \frac{C_2G}{1 + C_2G}\eta + \frac{1}{1 + C_2G}d \quad .$$

To analyze this we consider the extreme case when $H = G$, that is, we have a precise model of the plant. The expression is simplified to

$$Y = \frac{C_1 G}{1 + C_1 G} Y^* - \frac{C_2 G}{1 + C_2 G} n + \frac{1}{1 + C_2 G} d \quad .$$

It is easy to see that the design consideration of command following is completely decoupled from that of reduction of sensitivity to the measurement noise. Even when the model does not exactly match the plant $G$, which is almost always the case, the extra parameter introduced by $C_1$ still provides more freedom in design than the classical approach.

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